Hydrobiologia **220**: 189–204, 1991.

Effects of oil/gas field produced water on the macrobenthic community in a small gradient estuary

James M. Nance
National Marine Fisheries Service, Southeast Fisheries Center, Galveston Laboratory, 4700 Ave. U, Galveston, TX 77551, USA

Received 3 April 1990; in revised form 13 November 1990; accepted 10 December 1990

Key words: produced water, hydrocarbons, oil pollution, macrobenthos, estuarine

Abstract

Little is known about how climatic events (i.e., drought) inhibit or enhance movement of petroleum hydrocarbon laden sediments in estuarine systems and how this in turn effects the macrobenthic populations exposed to these sediments. Seventeen collection stations were established and monitored at New Bayou, Texas, a small gradient estuary which receives petroleum products via oil/gas field produced water discharge. Hydrographic, geologic and biotic samples were taken monthly from each station during a period of reduced rainfall.

Both temperature and dissolved oxygen data taken during the study followed patterns typical for the area. Salinity values increased into the polyhaline range at near-bay stations during the reduced rain period, while upper bayou stations remained within the oligohaline range.

Sediment grain sizes along the bayou were generally in the silty-clay range. Sediment hydrocarbon concentrations were highest (11.4 mg g^{-1} dry sediment) around the produced water discharge site and lowest at near-bay stations (0.2 mg g^{-1} dry sediment). Ninety-six macrobenthic species were collected during the study. General effects from produced water discharge on macrobenthic populations followed the classical pattern outlined by other research in shallow bay systems. A sediment hydrocarbon concentration of 2.5 mg g^{-1} dry sediment was found to reflect the average value needed to depress population abundances. Both abundance and diversity values were lowest at central stations near the discharge site. This zone of depressed macrobenthic populations extended from the discharge site at least 107 m downstream and 46 m upstream. The zone of stimulated macrobenthic populations occurred 1486 m downstream and 381 m upstream from the discharge site.

Introduction

Along the upper Texas coast petroleum exploration and recovery is often associated with salt domes in the Gulf Coast geosyncline. Geological formation water affiliated with petroleum from these areas is characteristically high in dissolved solids (Hunt, 1979). When petroleum is extracted from reservoir rock, the salty water (brine) associated with petroleum is also taken. This 'produced water' is separated from petroleum products and then usually discharged into the nearest surface water system. Separation of petroleum products from produced water is not 100% complete, and thus some quantity of petroleum hydrocarbons is also discarded with the produced water

(Jackson *et al.*, 1981, Lysyj, 1982). The brine solution quickly diffuses and is not toxic to organisms (Harper *et al.*, 1985), but the associated petroleum hydrocarbons are toxic in most cases (Baker & Crapp, 1971; Nelson-Smith, 1973; Neff *et al.*, 1976; Rice *et al.*, 1977; Neff, 1979). These petroleum hydrocarbons are adsorbed to silt and clay particles and carried to the bottom sediments where they accumulate. If accumulations reach a sufficient concentration, destruction of macrobenthic populations occurs.

Most research efforts to determine the effects of produced water on benthic communities around a discharge site have been directed towards large production platforms located either offshore in deep water ($Z > 10$ m), or in large shallow estuarine bays ($Z < 10$ m). Harper *et al.* (1976, 1981) found little or no effects on the macrobenthos that were attributable to produced water discharge at the Buccaneer Oil/Gas Field. This field is located 50 km south of Galveston Island, Texas, in water that is 21 m deep. Middleditch and Basile (1978) and Middleditch *et al.* (1977, 1979) showed that sediments and sea water around the production platforms contain only small amounts of alkanes (the maximum was 25 ppm in some of the sediments). The Gulf Universities Research Consortium's study off the Louisiana coast yielded similar results (Ward *et al.*, 1979). They concluded that seasonal changes in temperature and salinity had a far more significant effect on species diversity and population abundance of marine life than did the presence of low-level concentrations of oil. None of the investigators found any effects on the benthic organisms they studies that were attributable to oil production in the area (Farrell, 1979; Kritzler, 1979; Waller, 1979). Studies on benthic communities under California platforms (Carlisle *et al.*, 1964; Bascom *et al.*, 1976) and near platforms in Venezuela (Templeton *et al.*, 1975) concur with the results of these studies. It appears that because of the greater potential for mixing in deep water ($Z > 10$ m), the hydrocarbons are not easily incorporated in the sediments.

Destruction of benthic populations has been noted around production platforms in shallow water ($Z < 10$ m) (Mackin, 1971, 1973; Armstrong *et al.*, 1979). Zones of effect were clearly recognizable around these platforms where the hydrocarbons had become incorporated in the sediments. The first zone was one in which there was near total defaunation of all benthic organisms. It is characteristic of this type of toxic pollution that, while there are definite differences in tolerance of different groups and species, all are susceptible. There is no indication that produced water pollution may be stimulative in heavy concentrations to any of the benthic groups (Mackin, 1973). This is markedly different from biological pollution, where a few animals that are adapted to living in low oxygen, thrive (Reish, 1959; Gilet, 1960; Reish, 1964; McLusky *et al.*, 1980).

Outside the small area enclosed by the first zone of total destruction was a transition zone. In this second area there was a depression of both species and abundance of the benthic organisms. This zone may be the first zone encountered at a discharge site, if the concentration of the sediment hydrocarbons is not of sufficient quantity to totally destroy the benthic populations. The third zone was an area of stimulation of all the marine communities. It appeared not to be a direct stimulation from the brine discharge, so far as the macrobenthic populations were concerned, but appeared to directly stimulate bacteria, yeasts, fungi and phytoplankton species which are fed upon by the benthos (Mackin, 1973). Mackin (1950) first noted this stimulation effect in his work on oyster growth rates and brine discharge. Minter (1965) described similar results in holding ponds for refinery wastes in Oklahoma. Zones of stimulation have also been observed by investigators working with other types of pollutants (Blegvad, 1932; Filice, 1954a, 1954b, 1959). These also appeared to be areas of a stimulated bacteria community.

Little research effort has been directed towards the effects of produced water on benthic populations in small stream-like bayou systems. It was the purpose of this research to: 1) determine if the chronic input of petroleum hydrocarbons in a small gradient bayou impacted the benthos near the discharge site; 2) detect how this depressed area affected the complex meshing of the three communities (i.e. marine, estuarine and freshwater) found in such a bayou system; and 3) determine how this impacted area shifted or changed through various seasonal abiotic cycles and major climatic events.

Materials and Methods

Many small gradient estuaries along the upper Texas coast are discharge sites for produced water. New Bayou is one such estuary, and was the site chosen for this study.

Description of the study site

New Bayou is a small gradient estuary located in Brazoria County, Texas. It empties into Chocolate Bay, which is near the northwest end of West Galveston Bay. Water flow from the mouth of New Bayou is a composite of water from a confluence of three bayous in the area. New Bayou has its origin near Alvin, Texas, while Mustang Bayou, the largest of the three, passes through Alvin and has its origin another 40 km to the northwest near Missouri City, Texas. Persimmon Bayou is the smallest of the three and is in reality just part of Mustang Bayou. There seems to be some confusion as to the name of the lower end of 'New Bayou'. Some literature (Moffett, 1975) refers to it as Mustang Bayou, while others (Ray, 1978) refer to it as New Bayou. In this study it will be referred to as New Bayou (NOAA Nautical Chart 11322).

A typical salt marsh habitat borders the lower 5 km of New Bayou, with *Spartina* being the dominant shore plant in this area. As one moves upstream, this marsh habitat is gradually replaced by the typical mixture of Gulf Prairie and Post Oak Savannah type vegetation characteristic of southeastern Texas (Gould, 1975). Agricultural interests in the area have converted much of the land in the upper areas along New Bayou into various types of crop production sites.

Produced water is discharged into the bayou system 4.5 km upstream from its mouth. General Crude Oil Company started gas production in the area in the early 1960's. Mobile Oil Company took over this production in the late 1970's. Overall, about 500 000 liters of brine per day have been discharged into New Bayou from this production effort; a relatively low rate of disposal compared with most petroleum operations in the coastal area. 85 to 90% of the brine discharged into the New Bayou system comes from the T. Martin No. 5 gas well (Ray, 1978).

Field procedures

Preliminary sampling revealed that the three biological zones, common to shallow bay produced water discharge sites, were present along New Bayou. Seventeen stations were established to ascertain the effects of produced water discharge on the macrobenthic invertebrate community through seasonal abiotic changes (Fig. 1). Stations were established at very close intervals around the discharge site, so that any changes within the biological zones, or movement of petroleum laden sediments, could be monitored (Table 1).

Each of the seventeen stations was sampled during the last week of each month commencing in May 1980 and terminating in April 1981. During each sampling cruise a 5 m john boat was positioned on station by land sightings and all samples were collected while the boat was anchored in the center of the bayou (average bayou width was about 20 m). Four benthic samples were collected at each station with an Ekman grab having a total area of 232.26 cm^2 (15.25 cm × 15.25 cm). The first three samples were washed separately on a 0.5 mm mesh screen, placed in labeled jars and fixed in a 10% formalin – bayou water solution. A sediment sample was taken from the fourth grab sample by scraping the upper 5 cm of substratum into a plastic whirl-pak bag. The sample was stored at 4 °C in the field and frozen immediately upon returning to the laboratory. Field descriptions of the sediments

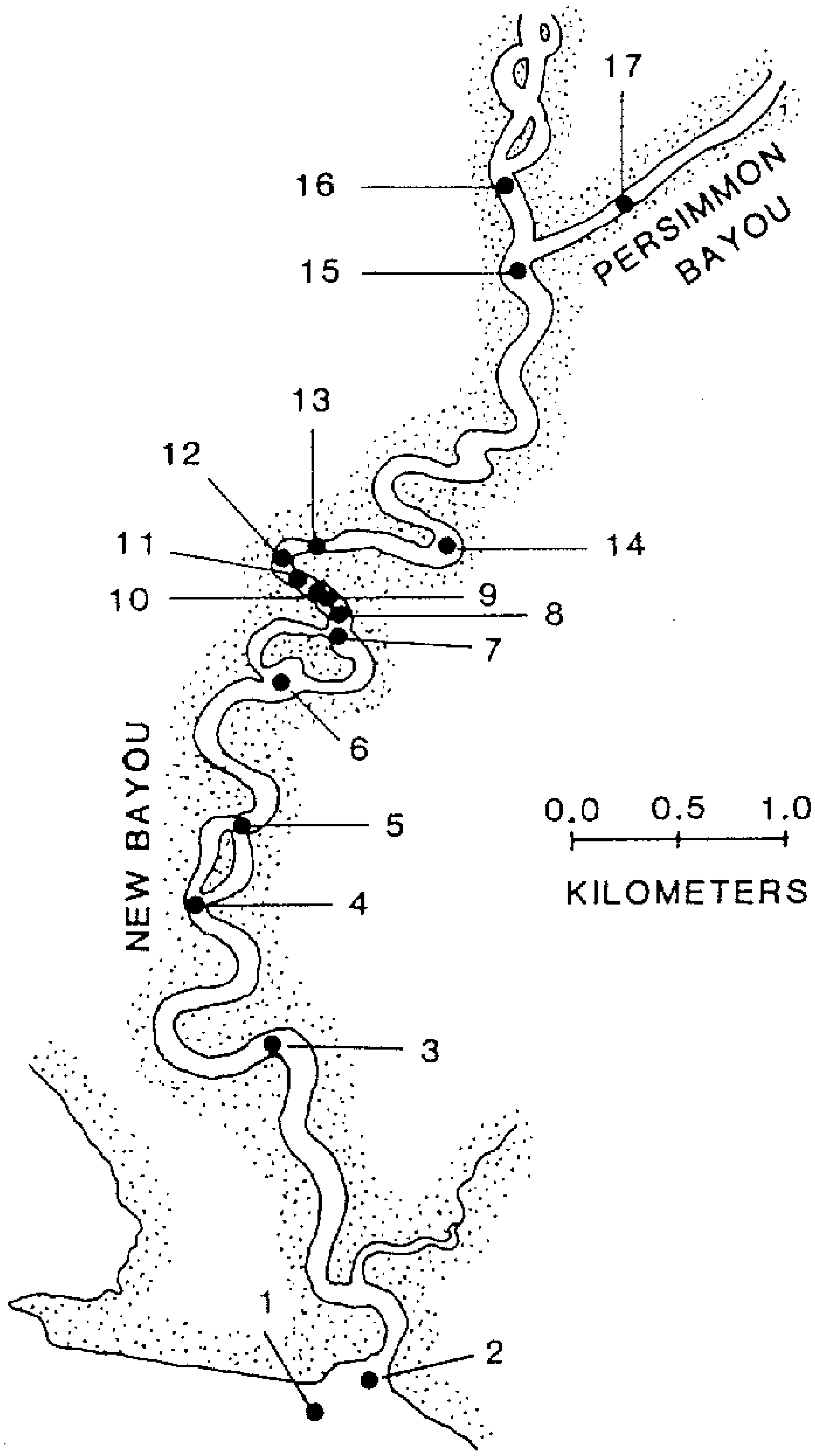

Fig. 1. Location of the seventeen stations at the New Bayou study site.

were recorded and a thermometer, placed in the upper few centimeters of sediment, was used to measure the temperature. Water temperature and salinity were measured at the surface and at the sediment – water interface with a YSI Model 33-S-C-T Meter. Dissolved oxygen concentrations from the same water depths were measured using a YSI Model 57 D.O. Meter with stirring probe. Water depth was determined at each station to within 0.15 m.

Table 1. Distance of the various sampling stations from the discharge site.

Stations	Distance from discharge
1	4686 m
2	4458 m
3	3048 m
4	1867 m
5	1486 m
6	610 m
7	213 m
8	107 m
9	61 m
10	0 m
11	46 m
12	182 m
13	381 m
14	952 m
15	2858 m
16	3353 m
17	3277 m

Laboratory procedures

Biological samples were washed in fresh water on a 0.5 mm mesh screen to remove formalin and any remaining sediment. The retained material was stored in rose Bengal stained 70% ethanol for at least 24 hours and then sorted. Organisms were identified to the lowest possible taxon, counted and preserved in 70% ethanol.

One half of the frozen sediment sample was used for both porewater salinity measurements and grain size analysis following the techniques of Folk (1980). Porewater salinity was measured with a refractometer after water and sediment were separated following sediment compaction. During grain size analysis the graphic mean, sorting graphic kurtosis, graphic skewness, and percentage of sand, silt, and clay were determined for each sample.

Hydrocarbon analysis was performed after the remaining frozen sediment sample half was thawed to room temperature, excess water drained off and 50 g of wet sediment placed in a 250 ml extraction flask. Dichloromethane, added to the extraction flask in 75 ml aliquots, was used to extract the hydrocarbons from the sediment.

For each aliquot the flask was stoppered, shaken vigorously for 5 minutes and then poured into a 500 ml beaker. Additional solvent aliquots were added until the solvent remained clear after the shaking period. The solvent in the beaker (usually about 375 ml) was poured slowly through a number 6 mesh glass fiber filter, concentrated with a rotary evaporator at 60 °C and then transferred to a vial to air dry at room temperature.

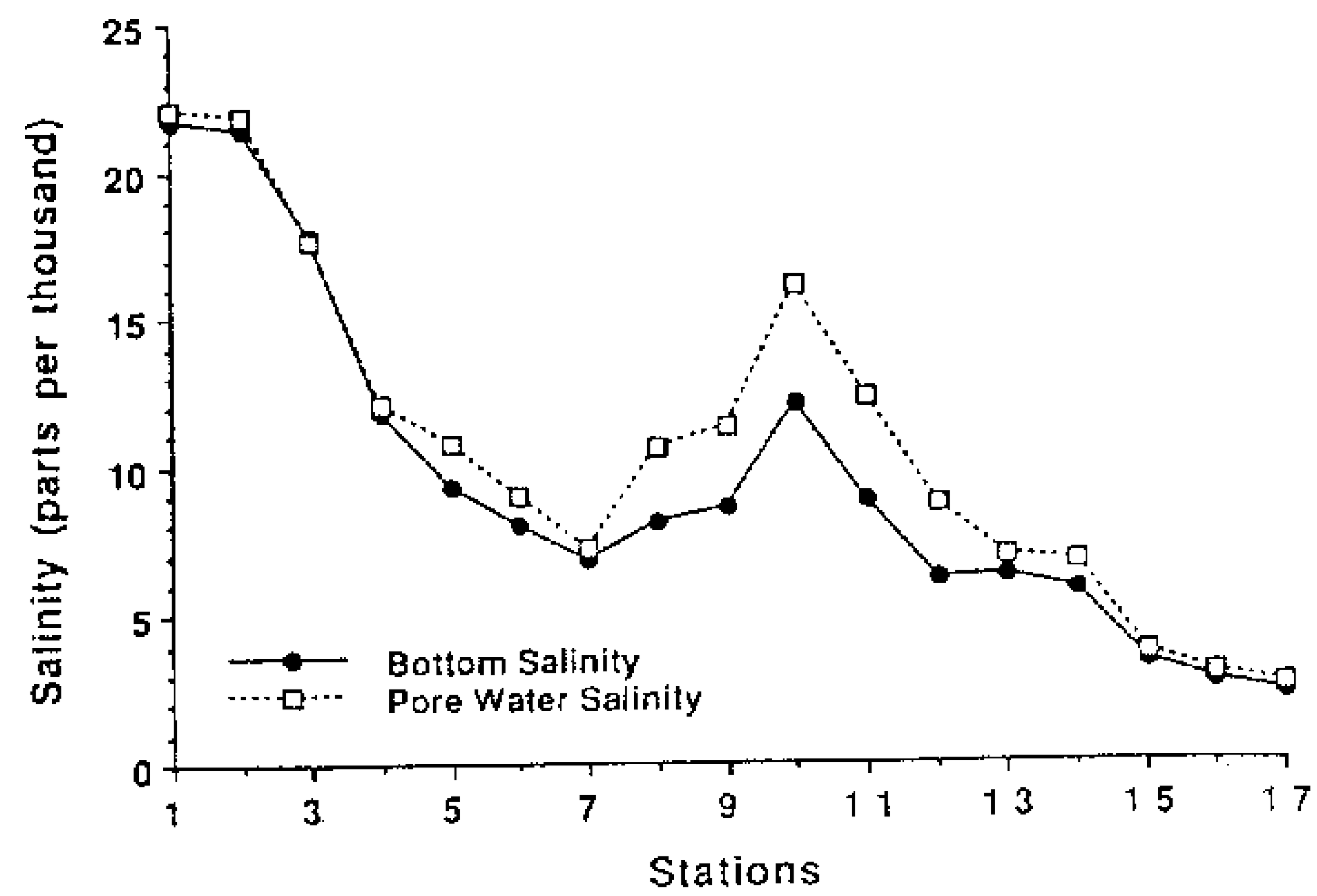

Fig. 2. Mean station salinities found at the study site.

Results

Abiotic data

New Bayou water temperatures and dissolved oxygen data emulated respective values shown for other similar bayou systems along the upper Texas coast (Potts, 1978; Wern, 1980). Temperature differences between surface and bottom waters were usually less than 1 °C. The warmest water temperatures (30 °C) along the bayou occurred during June and July, while the coldest water temperatures (11 °C) occurred during November and December. Mean bottom dissolved oxygen values were low (5.0 ppm) from May through September and high (10.0 ppm) from October through April. Bottom dissolved oxygen values were nearly always above hypoxic values (2 ppm) at individual stations. The exceptions were stations 14 and 15, which experienced hypoxic conditions during August.

Average salinity values steadily decreased from the bay to inland bayou sites (Fig. 2). Bottom water and porewater salinities were polyhaline (18.0–30.0 ppt) at stations 1, 2 and 3, while stations 15, 16 and 17 had oligohaline salinities (0.5–5.0 ppt). Stations 8–12, although in the mesohaline salinity range (5.0–18.0 ppt) with the other central stations, were elevated somewhat because of the brine discharge near station 10. Surface water salinity, which usually mimicked bottom water salinity at most stations, was on the average 5 to 8 ppt lower at these stations near the brine discharge. Produced water salinity levels remained at about 127 ppt throughout the study (mean = 126.8, SD = 6.3).

The amount of rainfall an area receives and the salinities of associated estuaries are inversely related. The period from April 1980 to April 1981, was extremely dry along the upper Texas coast (NOAA, 1980; NOAA, 1981). Only September 1980 had a positive departure from normal value during this period (Table 2). Interstitial salinities, which depict average salinity values and not daily fluctuations experienced with tidal activities, increased along the bayou between May and September 1980, but decreased slightly during October 1980, following rainfall in September 1980 (Fig. 3). Salinities again began to increase from November through December 1980, how-

Table 2. Departure from Normal Precipitation for Each Month.

Month	Departure from Normal
Apr. 80	− 3.28 cm
May. 80	− 0.69 cm
Jun. 80	− 2.97 cm
Jul. 80	− 4.57 cm
Aug. 80	− 8.03 cm
Sep. 80	+ 10.64 cm
Oct. 80	− 7.54 cm
Nov. 80	− 4.88 cm
Dec. 80	− 8.26 cm
Jan. 81	− 0.74 cm
Feb. 81	− 4.72 cm
Mar. 81	− 3.43 cm
Apr. 81	− 3.94 cm

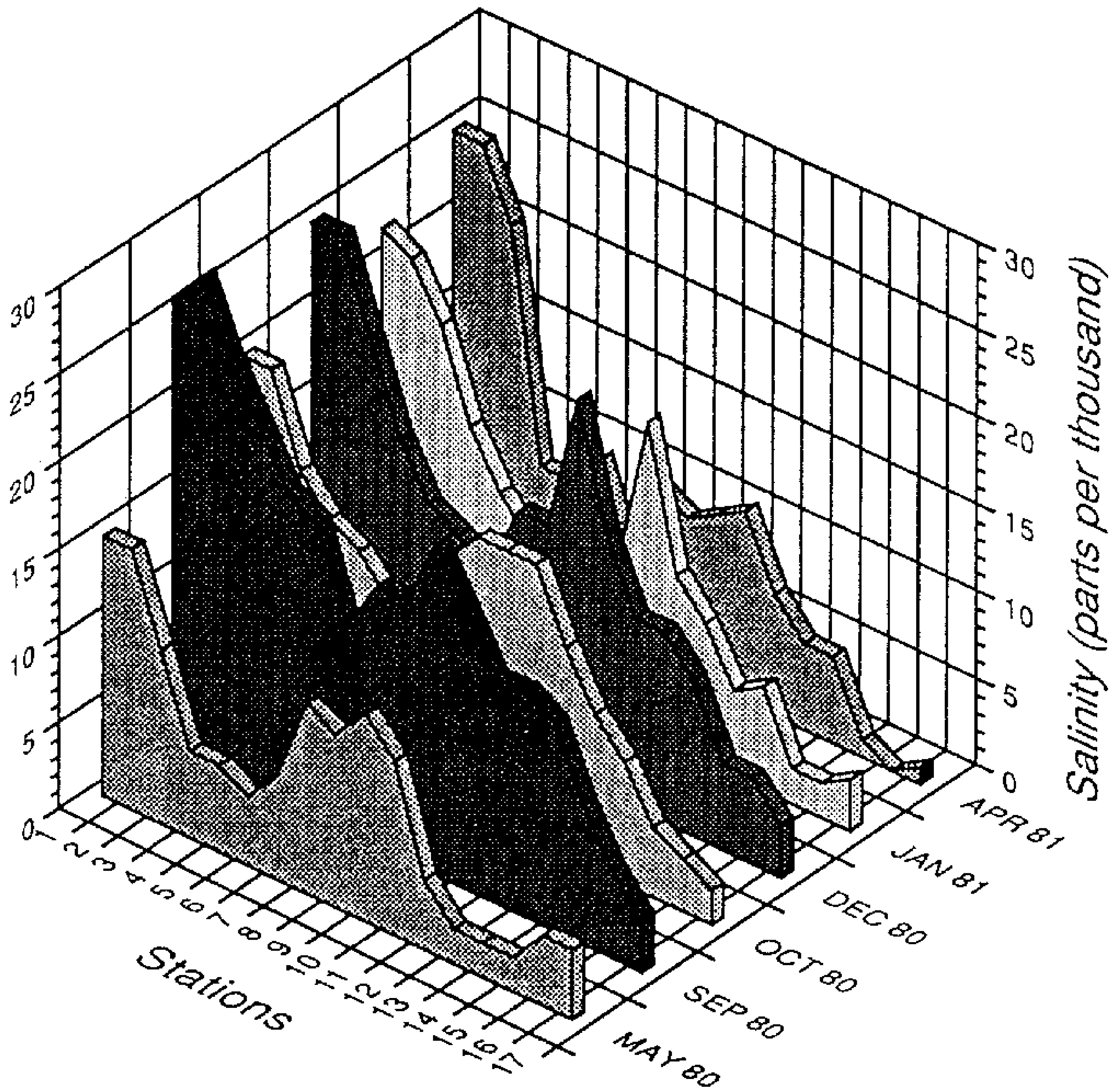

Fig. 3. Salinities found at the study site for selected months.

ever, near normal rainfall during January 1981 lowered salinities along the bayou. Salinities remained near this level during the remainder of the study (Fig. 3).

Sediment composition at the bayou stations progressively shifted from a silty clay mixture towards total clay during the period of below average rainfall. Suspended clay particles moved more slowly down the bayou because of the reduced flow rate and settled to the bottom along the bayou instead of being carried into the bay. By April 1981, sediments at all stations (except station 1) were composed of at least 50% clay. Sediments at the central stations near the discharge site were composed of more than 75% clay probably because of increased flocculation in that area. Flocculation of clay particles passing from areas of low salinity to areas of higher salinity have been described in other research (Postma, 1967).

Hydrocarbon levels exceeded 2.0 mg/g dry sediment only at stations 8–12 between May 1980 and April 1981 (Fig. 4). The greatest hydrocarbon concentration 11.4 mg g^{-1} of dry sediment) occurred at station 9 in October 1980. Station 9 usually had more hydrocarbon per gram of sediment than any of the other stations, with station 10 having the next greatest amount. This trend indicated that the hydrocarbons associated with produced water discharge were carried only a short distance downstream before they were adsorbed on suspended sediment particles and settled to the bottom. It is interesting to note that during this period of reduced rainfall, stations 8 and 9, which had about the same hydrocarbon concentration in May 1980, were so dissimilar by April 1981.

All other bayou stations had significantly lower levels of hydrocarbons in the sediments in comparison with the central five stations. Hydrocar-

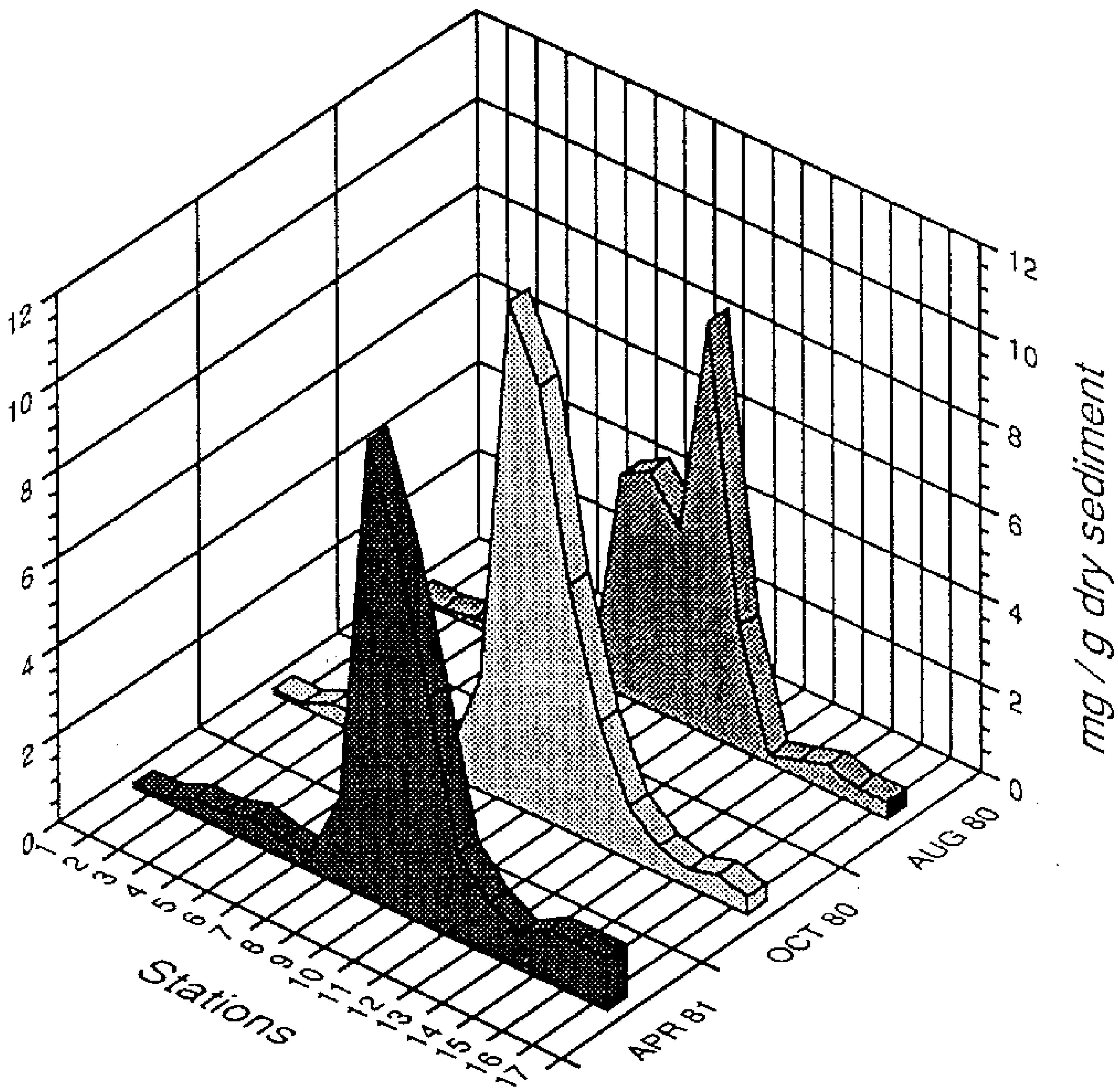

Fig. 4. Hydrocarbon concentrations at the study site for selected months.

bon levels at stations 1–7 were generally below 0.2 mg g^{-1} of dry sediment. No general increase or decrease in total sediment hydrocarbon concentration was noted for these station during the period. Upstream stations (stations 13–17) had hydrocarbon levels similar to those exhibited by stations 1–7 at the onset of the study, but ended (April, 1981) with elevated hydrocarbon levels (1.2 mg g^{-1} of dry sediment). Reduced runoff and increased penetration of tidal activities up the bayou were probably responsible for pushing hydrocarbons into this region.

Biotic data

Ninety-six species were collected during the study. This species richness value is comparable with results obtained during other studies in soft-bottom low salinity Gulf of Mexico areas (Mackin, 1971; Dugas, 1978; Wern, 1980). Polychaeta was the most abundant taxon (71%), followed by Oligochaeta (20%) and Isecta (5%).

Temporal variations in community composition were noted at New Bayou. Abundance values were generally greatest during the late winter to early spring and lowest during the late summer to early winter (Fig. 5). No fall peak occurred as was noted by Wern (1980) at Sea Rim State Park, Texas. The single abundance peak in February followed the typical monocyclic pattern shown during other research in this habitat type along the upper Texas coast (Mackin, 1971; Harper, 1973; Potts, 1978). Species diversity (H′ = Shannon – Wiener diversity index value) generally followed the same trend (Fig. 5). Peak diversity occurred during the late winter to early spring, while lowest diversity was noted during the late fall to early winter.

Spatial variation with respect to benthic popu-

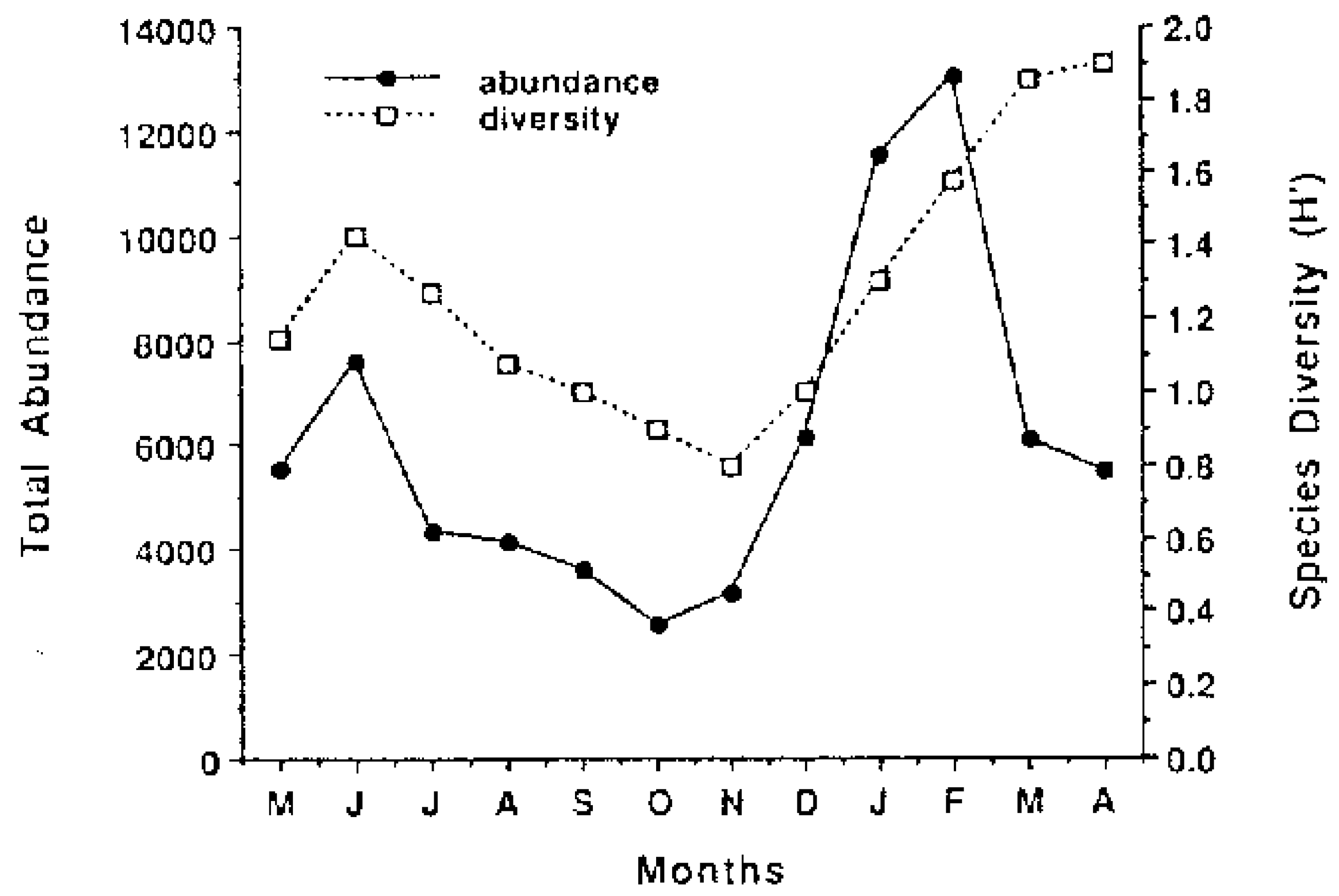

Fig. 5. Monthly species abundance and diversity at the study site.

lations was also observed at New Bayou. Abundance values for each of the seventeen stations exhibited a general trend of decreasing abundance from the bay to upstream sites (Fig. 6). Stations 1 and 2 exhibited the highest abundance values, while stations nearest the produced water discharge site (stations 8–11) exhibited the lowest values. All other stations were quite similar in abundance.

Mackin's (1971) generalized model of the effects of produced water discharge on macrobenthic communities in shallow bay systems was almost classically reproduced in this study. Only the zone of total destruction was not present at New Bayou. Station 10, about 10 m from the discharge site, seemed to have been far enough away from the maximum hydrocarbon zone to allow some organism to survive; 23 total individuals were collected during the year, with *Streblospio benedicti* being the most abundant species (8 individuals). The zone of depression extended from the discharge site at least 107 m downstream and 46 m upstream. Station 12, at 182 m upstream from station 10, was affected, but not to the same extent as stations 8, 9 and 11. The average monthly abundance at stations 8, 9 and 11 was 34 individuals while it was 162 at station 12. The zone of stimulation occurred 1486 m downstream at station 5 (average monthly abundance of 615) and 381 m upstream at station 13 (average monthly abundance of 338). The high abundance values at stations 1 and 2 were not areas of produced water stimulation, but were areas of increased marine influence. Average monthly abundance at these two stations was 1045.

Five significantly different abundance site groups were detected by Duncan's multiple-range test (Sokal & Rohlf, 1976) (Fig. 7). Stations 1 and 2, the most marine influenced, grouped out together and had significantly higher mean abundance values than all other stations. Stations 3–7 and stations 12–17 composed the second group. Although there were five subgroups within this second major group, extensive overlapping of these subgroups prevented any conjecture as to significant differences in abundance between

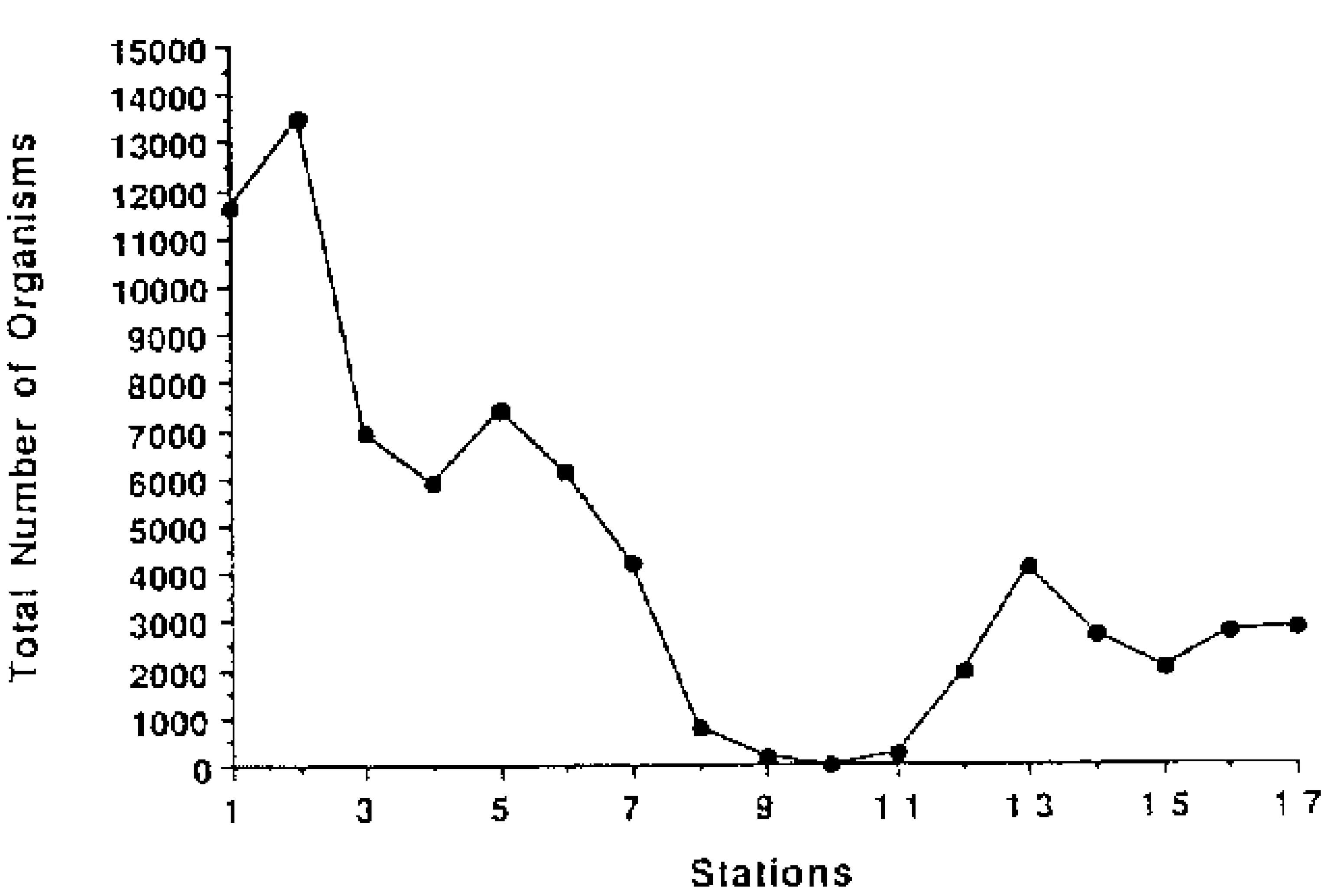

Fig. 6. Species abundance at each station during the collection period.

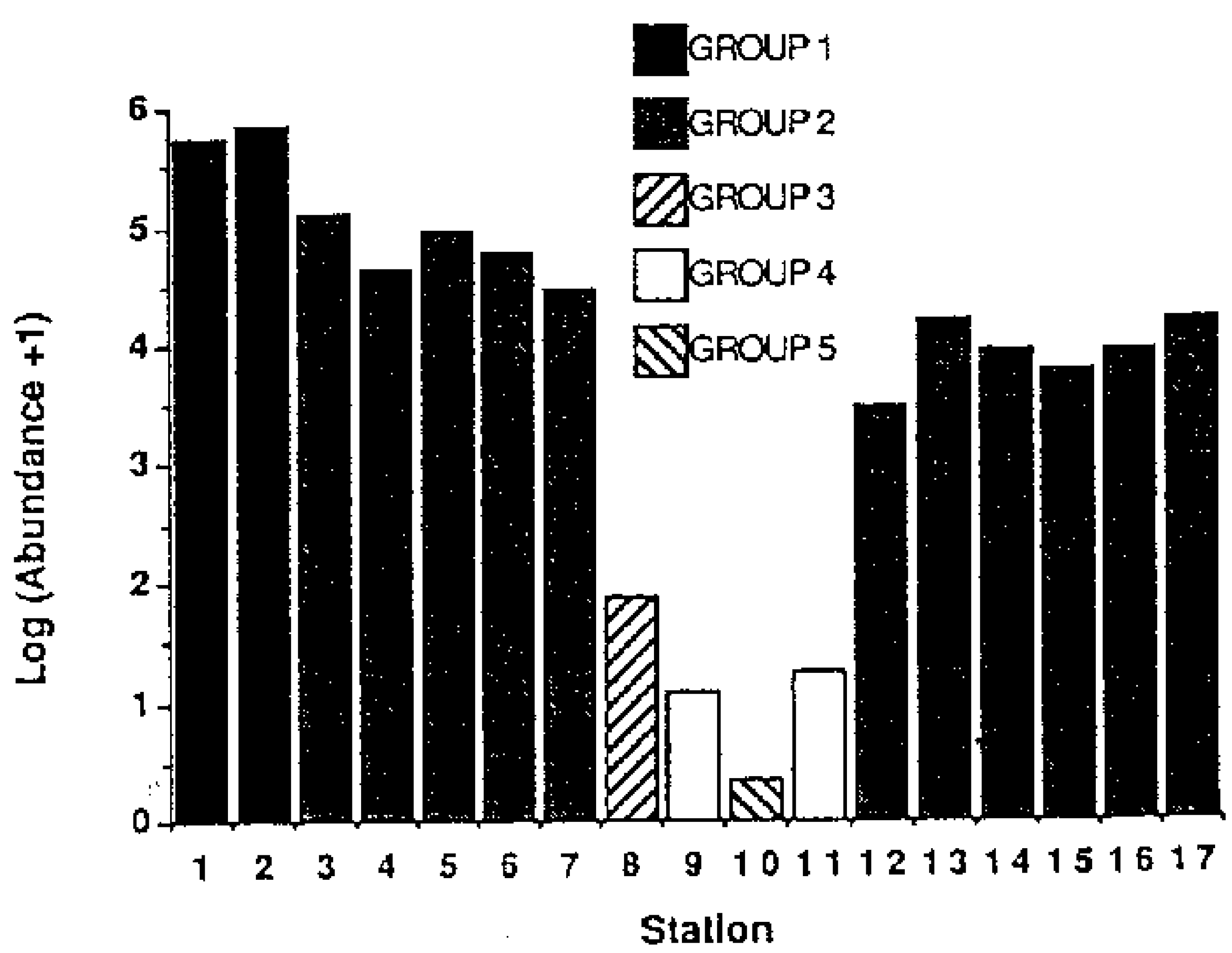

Fig. 7. Results of Duncan's multiple range test for each station using species abundance data.

stations. Station 8 composed the third group. Abundance values at this station were significantly greater than at each of the other brine-influenced stations, but less than all other stations. Station 8 seemed to be the downstream edge of the zone of depression. Stations 9 and 11 composed the fourth group of similar stations. These two stations seemed to be well within the zone of depression. Station 10 formed the fifth and final station group. This station, near the zone of total destruction, had significantly lower abundances than all other stations along the bayou.

Species richness values at each station (Fig. 8) followed the same general pattern established by species abundance values (Fig. 6). Stations 1, 2 and 3 had the greatest number of species (each with more than 40). Stations 8, 9 and 11 all had species counts of less than 20, while station 10 had the least number of species with 7. All other stations had species richness values ranging between 25–35.

Diversity index values (H') followed a slightly different pattern (Fig. 8). Stations 1–7 all had similar average H' values at around 1.6 (with the exception of station 3 with a value of 2.0). There occurred a sudden drop in average values between stations 7 and 8 at the zone of depression. Values continued to drop to a nadir at station 10 (average $H' = 0.15$). Diversity index values rose continuously from station 10 to station 17. Station 17 had the highest average H' value at 2.05. It is unusual for a freshwater influenced area to have higher H' values than an estuarine area (Boesch, 1973). The bay influenced stations did have higher numbers of species than the freshwater stations, but higher evenness values gave the upstream stations the higher H' values.

Duncan's multiple-range test results showed four major significantly different station groups using average H' values (Fig. 9). Group I was composed of all stations located outside of the zone of depression. Six subgroups were present in this major group, but were not significantly different because of overlap. Group II contained only station 12; the station just on the upstream edge of the zone of depression. Station 8 and 11, within the zone of depression, constituted the third group. Average H' value at these stations was only 0.58. Stations 9 and 10 comprised the final group. These two stations were well within the zone of depression. Diversity index values averaged only 0.21 at these two stations.

Numerical classification (or cluster analysis) was performed by station (site) following methods outlined by Clifford & Stephenson (1975). Cluster analysis delimited three distinct station groups and four distinct species group (Fig. 10). Species group I was composed of those species that were most common in the oligohaline water habitats

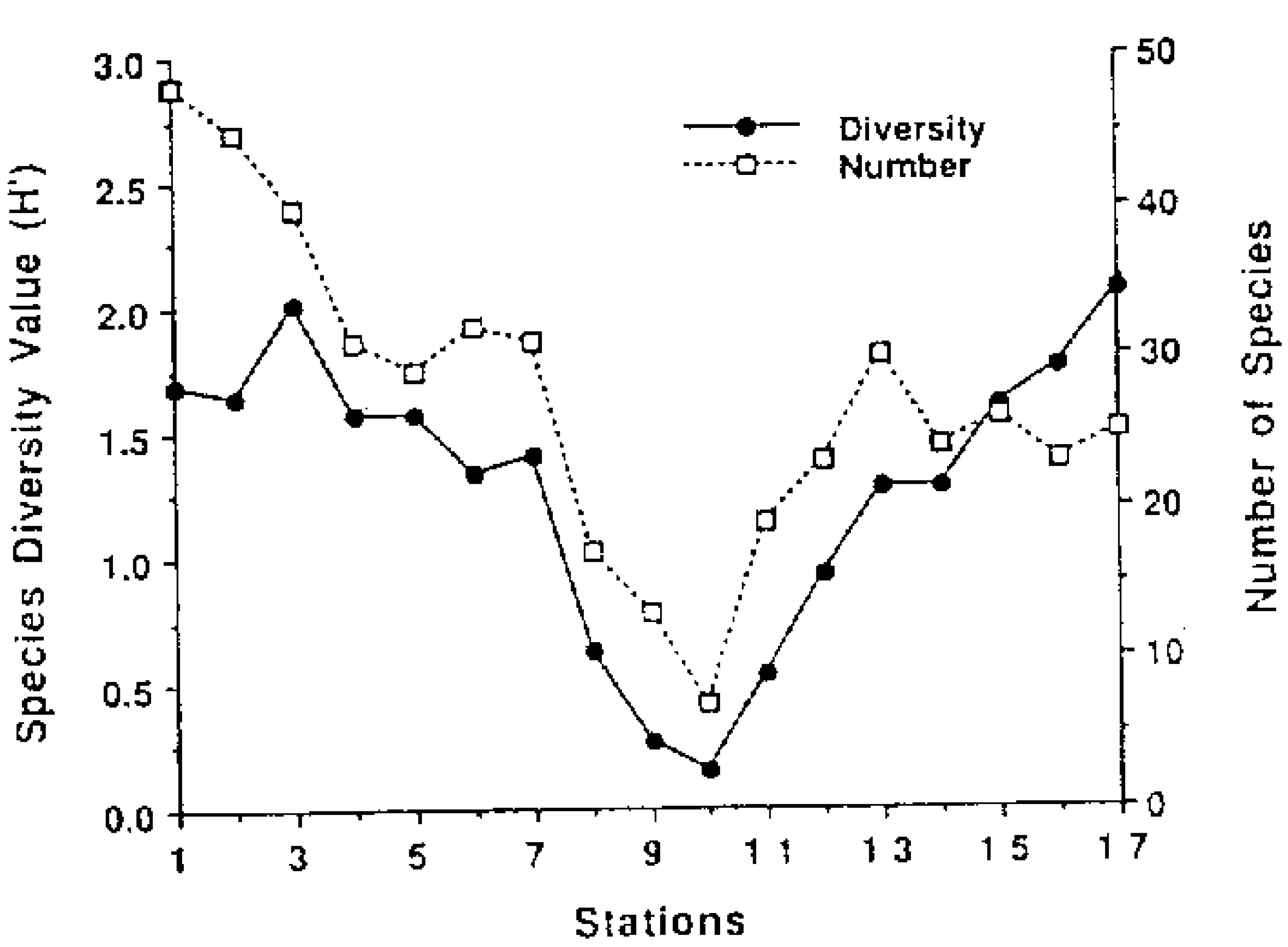

Fig. 8. Average diversity and total number of species for each station.

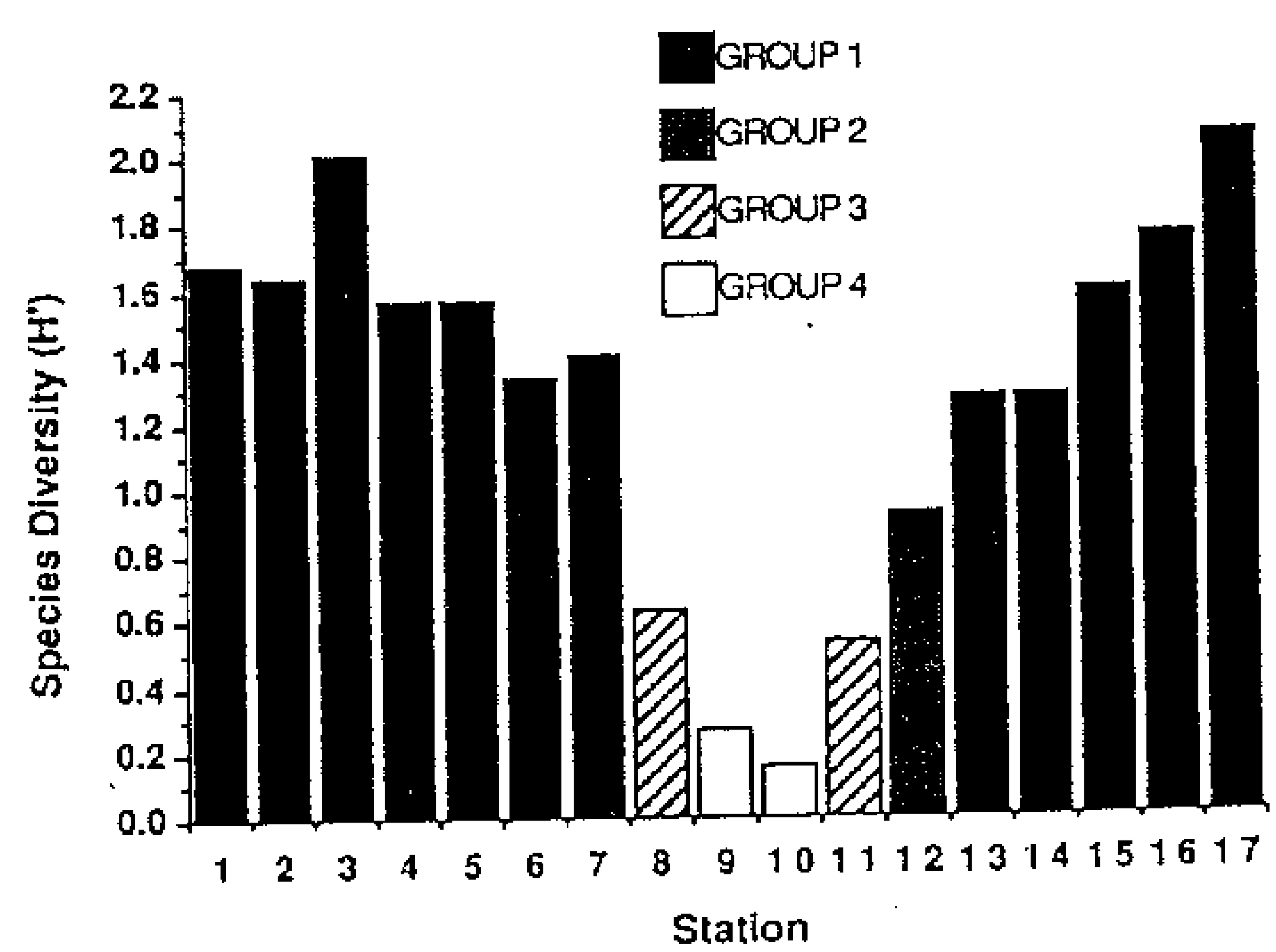

Fig. 9. Results of Duncan's multiple range test for each station using species diversity data.

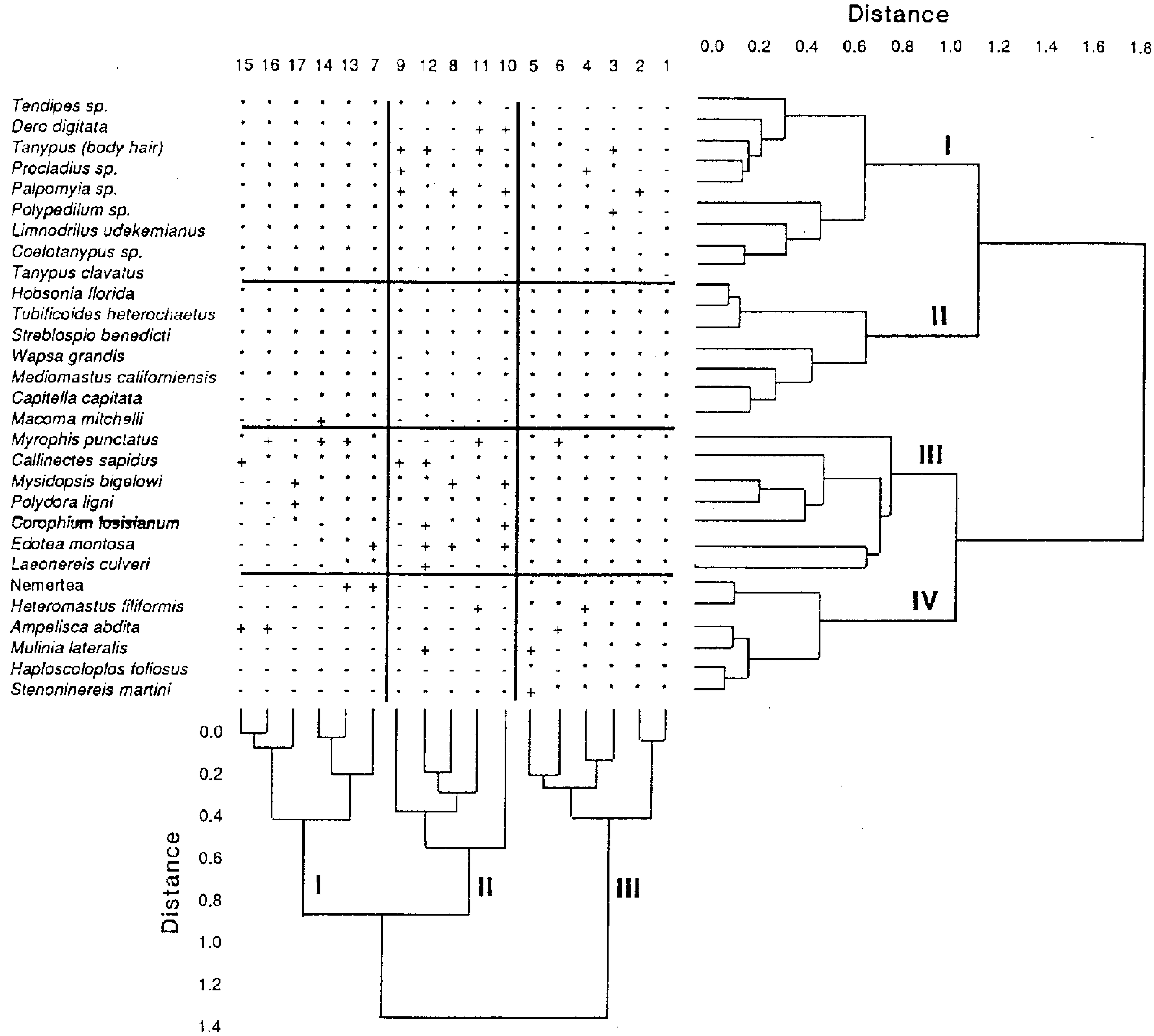

Fig. 10. Station and species group dendrograms for numerical classification. Each station and species group is designated by a Roman numeral. Symbols represent the degree of correlation between elements (* = strong, + = moderate and − = weak).

along the bayou. The group included 7 species of chironomid larva and 2 species of Oligochaeta. Individuals from these species dominated the communities at those stations forming station group I (station 7 and stations 13–17). Species group II contained all the ubiquitous species of the unpolluted areas of New Bayou. Of the seven species found in this group, four were polychaetes, two were oligochaetes and one was a bivalve. Only *Capitella capitata* and *Macoma mitchelli* were not found in great abundance at every unpolluted station. The stations near the produced water discharge site (stations 8–12) comprised station group II because they lacked large numbers of these ubiquitous species. These stations were all within or at the edge of the zone of depression. Species group III was formed by those species that occurred mainly in the marine influenced area, but also to a lesser extent in the fresher upstream areas. These organisms were common, but never overly abundant at all the marine stations (station group III). Species group IV was composed of those species that were found only at the marine influenced stations. The species found included 3 polychaetes, 1 nemertean, 1 bivalve and 1 amphipod.

Four separate station groups were obtained with principal coordinate analysis (Clifford & Stephenson, 1975; Pielou, 1984) (Fig. 11). Group I was composed of the six stations closest to the bay. A continuum of changing factors was depicted from the two bay stations (stations 1 and 2) towards station 6. Group II was composed of the stations within or near the zone of depression (stations 8–12). Station 7 and stations 13 and 14 formed group III. This group was similar to group II with respect to most abiotic factors, but not with respect to hydrocarbon concentrations. Values along axis 1 were very similar, but stations in group II had positive axis 2 values, while stations in group III had negative values. Thus, the stations in group II and III were more similar in certain abiotic and biotic factors than one would have gathered by numerical classification alone. Group IV was composed of the three stations which were farthest upstream (stations 15–17). These clustered out because of the greater freshwater influence expressed there.

Discriminant analysis (Smith, 1978) on abiotic and biotic data at New Bayou was performed to indicate which environmental variables may have been most important in establishing the species site groups detected in numerical classification and principal coordinate analysis. The abiotic variables of sediment mean grain size, sediment temperature, sediment salinity, sediment hydrocarbons, bottom salinity and bottom dissolved oxygen were used in this analysis. Axis 1, with 48.7%, and axis 2, with 42.2%, accounted for nearly 91% of the significant species group separation (Table 3). Variables along axis 1, which resulted in greatest group separation were sediment hydrocarbon (52.2%) and sediment salinities (24.2%). Along axis 2, separation was primarily in relation to the same two factors again, but in reverse order of importance. Sediment salinities provided 73.6% of the separation and sediment hydrocarbons provided 10.1%.

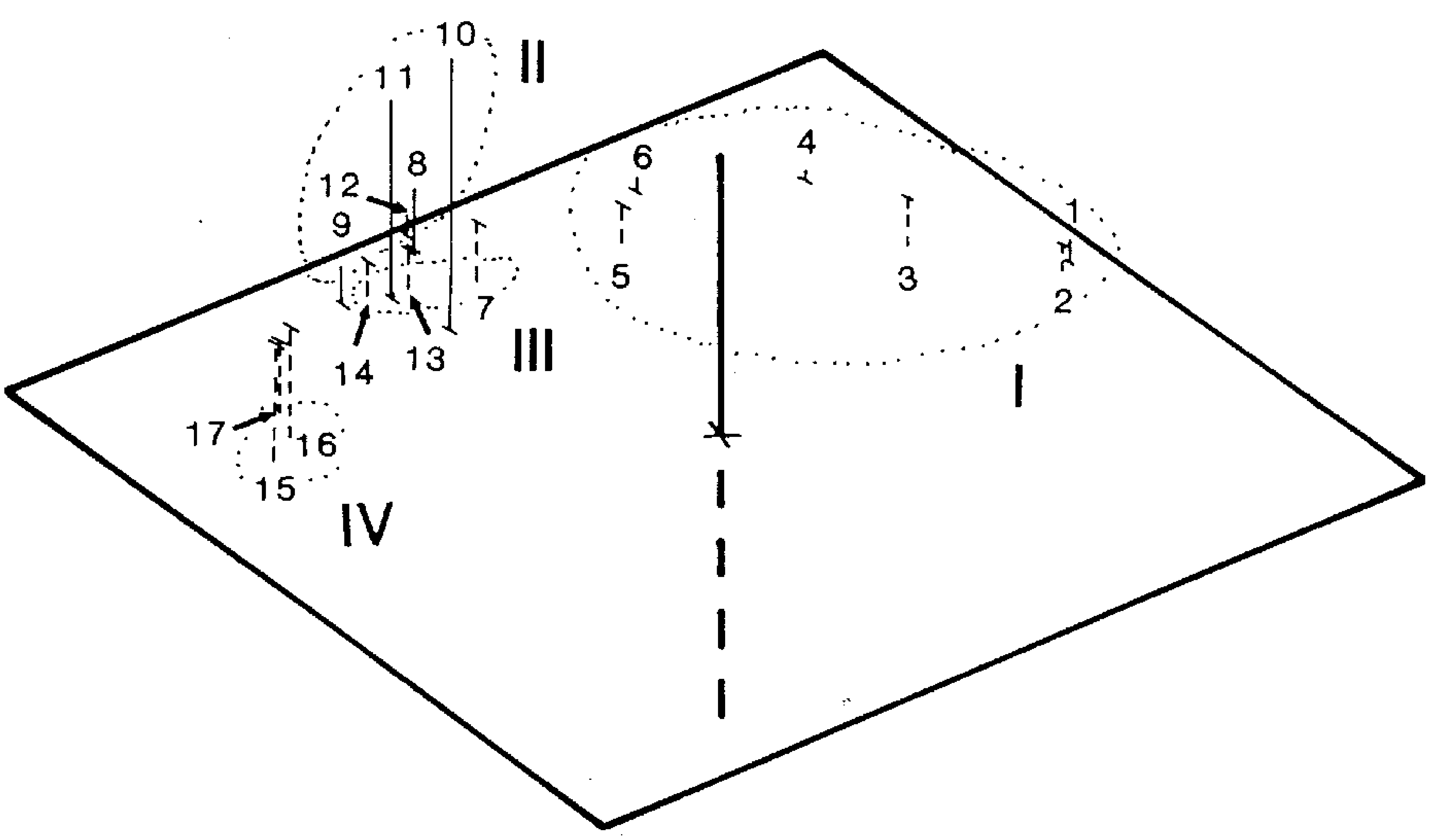

Fig. 11. Principle coordinate analysis for stations.

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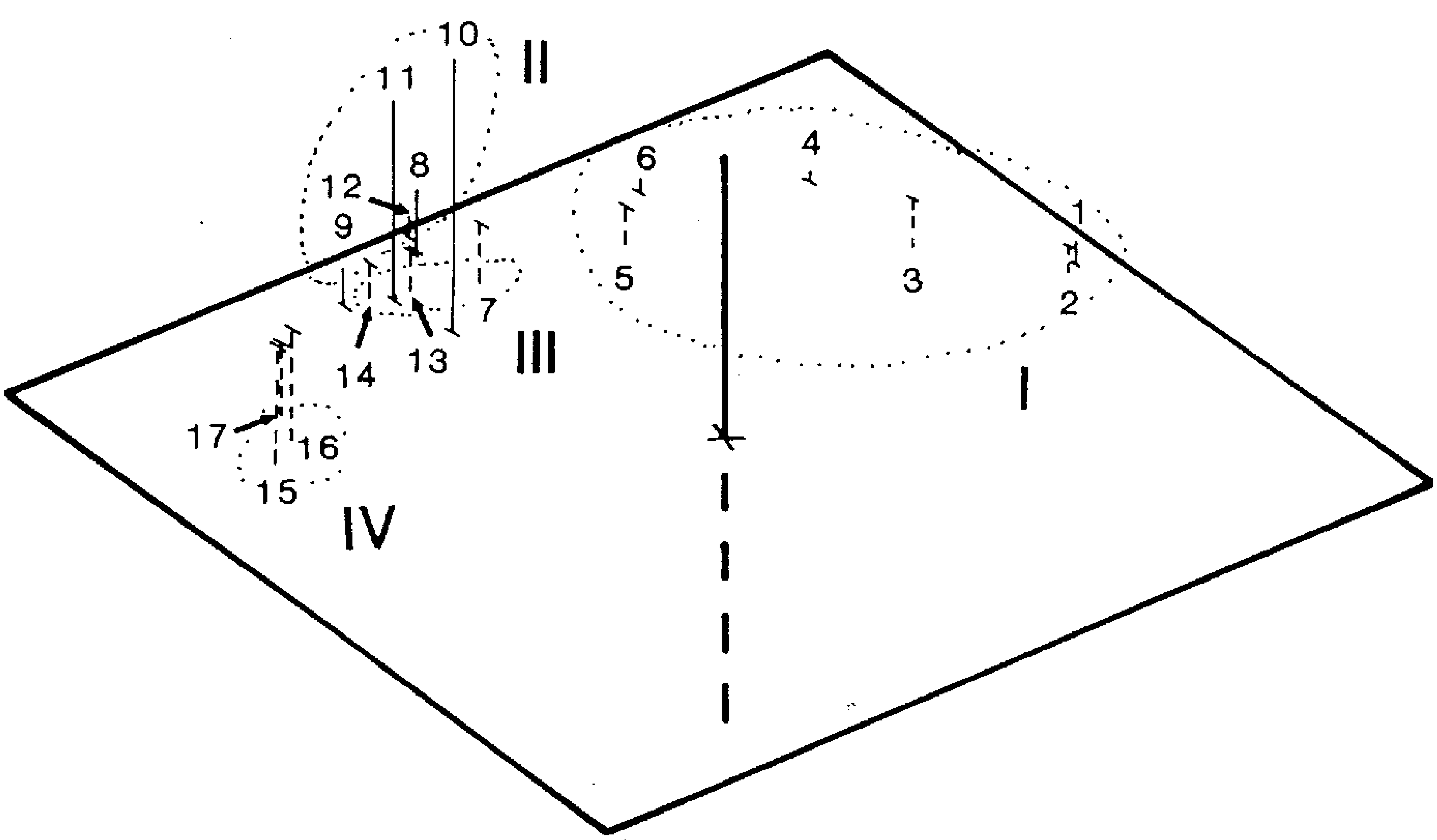

Fig. 11. Principle coordinate analysis for stations.

Table 3. Discriminant analysis results.

Amount of Significant Group Separation Accounted for by Each Discriminant Axis (Prob <0.05)

Axis	% Separation	Cumulative %	Chi-Squared	D.F.	Prob
1	48.7	48.7	10626.5	83	0.0001
2	42.2	90.9	9936.3	81	0.0001
3	5.8	96.7	2777.7	79	0.0001
4	1.8	98.5	1010.8	77	0.0001
5	0.9	99.4	552.1	75	0.0001
6	0.6	100.0	331.9	73	0.0001

Coefficients of Separation for Each Discriminant Axis

Variable*	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5	Axis 6
MGS	6.3	0.0	13.2	2.4	20.8	47.5
SEDT	4.8	7.3	18.1	24.3	4.9	31.3
BSAL	12.5	1.1	3.2	20.4	52.3	17.3
BDO	0.1	7.9	53.7	42.5	6.9	0.4
PSAL	<u>24.2</u>	<u>73.6</u>	1.7	1.5	13.2	2.7
OIL	<u>52.2</u>	<u>10.1</u>	10.0	9.0	1.8	0.7

* Key to symbols: MGS = mean grain size, SEDT = sediment temperature, BSAL = bottom salinity, BDO = bottom dissolved oxygen, PSAL = pore water salinity, OIL = sediment hydrocarbons

Discussion

New Bayou is typical of the numerous small stream-like estuaries found along the upper Texas coast. Mean temperatures and dissolved oxygen values followed the usual monocyclic pattern characteristic of the area, with greatest temperatures and lowest dissolved oxygen values in the summer and the inverse relationship true during the winter months. Species richness, at 96 species, was similar to what has been found during other studies in the region (Mackin, 1971; Wern, 1980), with Polychaeta the most abundant taxon. Peak species diversity and abundance occurred during the late winter to early spring, while lowest values were noted during the late summer to early winter period.

However, two events during the sampling period caused New Bayou to deviate from the generalized model of a typical upper Texas coast stream-like estuary. The first event was the below normal rainfall the area received, which caused an abatement in normal run off down the estuary. With the decreased freshwater flow through the system, salinities along the entire bayou increased, clay particles suspended in the water settled out in the bayou and were not carried out of the system, and tidal cycles were experienced in upper areas of the bayou. The second event that was of importance was the discharge of produced water into the bayou. This brine discharge caused high salinity water to be introduced into the bayou at an upstream location and caused an elevation of salinities in the localized area. Hydrocarbons associated with the produced water were also introduced into the bayou at the discharge site and it is the effect of these petroleum products on the benthic community that will be dealt with in detail in the remainder of the discussion.

The communities at New Bayou were primarily the product of environmental conditions. Jones (1950) suggested that temperature, salinity and substratum are the most significant factors determining marine benthic community structure. At New Bayou, during any one time interval, both temperature and substratum were very similar at all stations. Thus, it was salinity which played the major role in determining the extent of the three communities (marine, estuarine and freshwater) along the bayou. Discriminant analysis indicated that sediment hydrocarbon concentration and sediment salinity were the two most influential factors creating the community gradients along New Bayou. Although the sediment salinity gradient was the environmental factor that formed the grid and meshed the three community types together in the system, sediment hydrocarbon concentrations had the greatest single impact on community structuring at the study site. Hydrocarbon concentrations greater than 2.5 mg g^{-1} dry sediment seemed to disrupt or overshadow the effects of the salinity gradient in all cases. Regression analysis implied that sediment hydrocarbon alone accounted for 73% of the abundance variability in the system (Fig. 12). Stress overshadowed the natural structuring found in the system.

The four species groups determined from cluster analysis were significantly separated only along the lines of salinity, since all were equally absent from areas of high hydrocarbon concentration. Group I contained those species found in the more oligohaline-influenced areas. This group represented the freshwater community found at New Bayou. Species in this group were abundant only at stations that were typically oligohaline since this salinity level was near the upper range of their tolerance. Most species in this group were stenohaline, and thus were unable to invade the

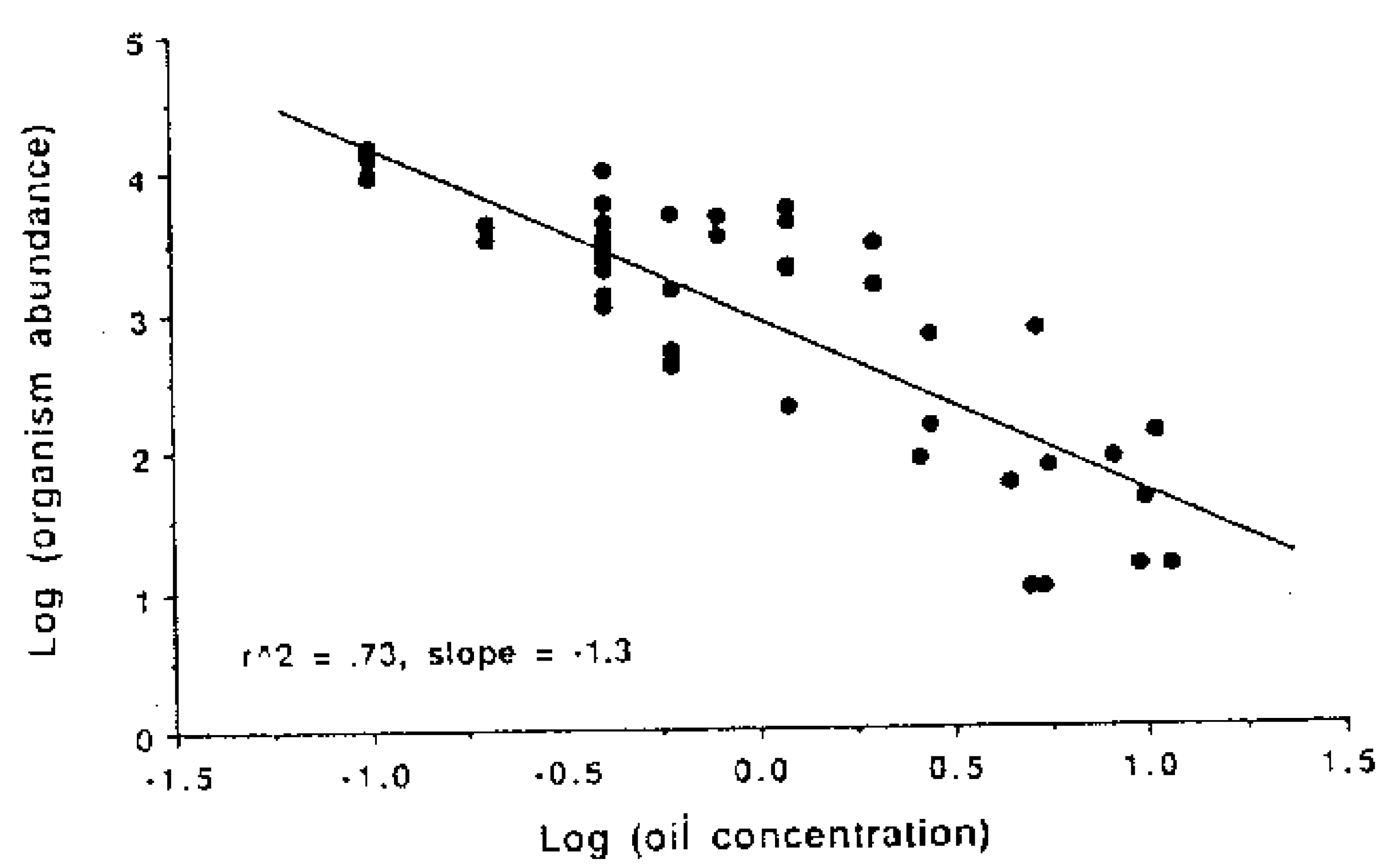

Fig. 12. Linear regression results of average abundance of organisms at various concentrations of sediment hydrocarbons.

higher salinity areas downstream. Group II was established by the ubiquitous species that occurred in large numbers. These represented part of the estuarine community at New Bayou. Most of these species were able to tolerate a great variety of salinities (euryhaline organisms). This species group overlapped the two other communities found in the area (i.e. marine and freshwater). These species were common at most stations, but were most abundant at stations in the mesohaline salinity range. Four species from this group accounted for 84% of the total abundance along the bayou. These included three polychaetes (*Hobsonia florida*, *Mediomastus californiensis* and *Streblospio benedicti*) and one oligochaete (*Tubificoides heterochaetus*). Members from the other two communities, being at the extreme ranges of their salinity tolerances, accounted for only a small fraction of the total abundance along the bayou. Group III was characterized by the ubiquitous species that occurred in moderate numbers. These species were mostly euryhaline crustaceans and represented another component of the estuarine community. Individuals of these species occurred at most stations in the mesohaline salinity range. Group IV was formed by the species which were found only in the most marine-influenced areas. These species were all stenohaline and composed the marine community at New Bayou. They were found only at stations that were in the polyhaline or upper mesohaline salinity range.

The station groups formed from cluster analysis and principle coordinate analysis were significantly separated along the lines of both salinity and sediment hydrocarbon concentration. Group I (stations 1–6) and Group II (stations 8–12) were separated from each other and the other stations with both of the statistical procedures. The former stations group represented the marine-influenced area along New Bayou, while the latter group represented stations that were under the negative influence of high concentrations of sediment hydrocarbons. The other six stations (stations 7, 13–17) were in either the lower mesohaline or oligohaline salinity range. The more oligohaline stations

(stations 15–17) were separated out from the other three using principle coordinate analysis, but all six stations were in the same group with cluster analysis.

Effects from sediment hydrocarbons at New Bayou followed the classical pattern described by Mackin (1971, 1973). As in shallow bay studies, areas of benthic community depression and stimulation were both well established at New Bayou. Areas characterized as within the zone of depression had an average sediment hydrocarbon concentration above 2.0 mg g^{-1} dry sediment. Moderate depression effects were observed at those stations that averaged hydrocarbon concentrations between 2.0–3.5 mg g^{-1} dry sediment, during the study, while major depression effects were observed at those stations that averaged hydrocarbon concentrations above 5.0 mg g^{-1} dry sediment during the year. Effects from 3.5–5.0 mg g^{-1} dry sediment could not be established, since these values were not observed during the study. Moderate effects at a station were characterized by average abundance levels between 720 and 2300 organisms/m^2, and average species diversity values between 0.6 and 0.9. Major effects at a station were characterized by average abundance levels below 190 organism/m^2 and average species diversity values below 0.5. Stations outside of the zone of depression had low levels of hydrocarbons in the sediment (below 2.0 mg g^{-1} dry sediment), had average species abundance levels above 4000 organisms/m^2 and an average species diversity value above 1.2.

Species diversity values obtained at the various stations at New Bayou were quite comparable with values obtained from other research. Wilhm & Dorris (1966), using the data from many investigators of freshwater and estuarine systems, reported that species diversity index values less than 1.0 were common when heavy pollution occurred. Values between 1.0 and 3.0 indicated moderate pollution, and values exceeding 3.0 characterized non-polluted water. However, Holland *et al.*, (1973) found that diversity index values above 2.0 indicated non-polluted water in the Galveston Bay estuary system. Similar diversity index values were obtained in the Neches River estuary, Texas (Harrel *et al.*, 1976) and at the Sea Rim State Park estuary system (Wern, 1980). Therefore, moderate pollution values in the Galveston area were estimated to be between 1.0 and 2.0, and anything over 2.0 was considered non-polluted water. Thus, even some of the New Bayou sites outside of the zone of depression seemed slightly stressed compared with other bay areas.

At New Bayou, results showed that the zone of depression was found at least 107 m downstream and no further than 182 m upstream from the discharge point. The area of depression might have been capable of extending further downstream, but the shallow water depth located at stations 5–7 may have presented a blockade to an unrestricted flow of hydrocarbons down the bayou (Fig. 13). Even during the period of decreased runoff, general bayou flow seemed strong enough to restrict the effects of the produced water discharge from traveling very far upstream. However, a slight increase in sediment hydrocarbon concentrations at the upstream stations was noted during the study. The increased penetration up the bayou by tidal activities was probably responsible for pushing the hydrocarbon laden silt and clay particles into this region.

The reduced runoff did seem to concentrate hydrocarbon settling into a smaller area than in the prestudy period. Levels of hydrocarbon were similarly high at both stations 8 and 9 at the beginning of the study. This indicated that both

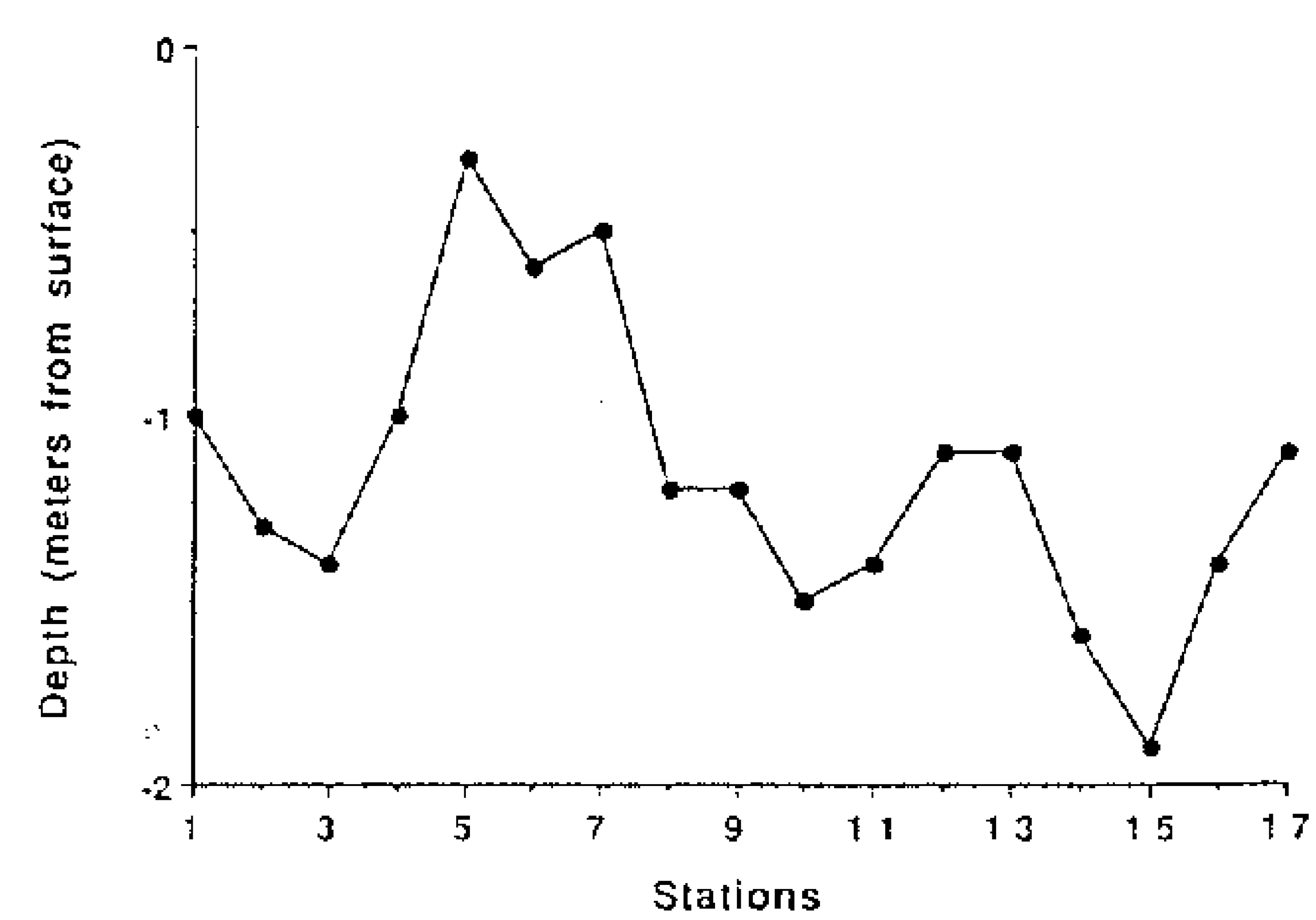

Fig. 13. Average water depth at each of the seventeen stations during the study period.

were well within the area of maximum depression at this time. Reduced runoff concentrated the settling of hydrocarbon laden sediments at shorter distances around the discharge site, and thus placed station 8 near the outer edge of the depressed area at the end of the study. Even with the decrease in sediment hydrocarbons noted at station 8, amounts were large enough to affect benthic populations in the area.

Zones of stimulation were found at least 1486 m downstream and 381 m upstream from the discharge site at New Bayou. Although the zones are visible in both the species abundance (Fig. 6) and species richness (Fig. 8) graphs, the values are not significantly different than the values from surrounding stations. However, levels of hydrocarbons in the sediments at the stations within the zone were elevated 0.2–0.3 mg g^{-1} dry sediment above surrounding stations outside of the zone of depression.

As pointed out by Harper (1986), the zone of enrichment (stimulation) usually involves a much larger area than the zone of depression. When average abundance data from this study at New Bayou was plotted using accurate scaled station distance intervals, it appeared that the zone of depression may have covered a linear distance of about 500 m, while the zones of stimulation may have covered linear distances of about 750 m upstream and about 1700 m downstream, a combined distance of around 2450 m. This meant the total zone of stimulation was approximately 5 times larger than the zone of depression. The calculated benthic loss within the zone of depression was 20 500 individuals, while the benthic gain within combined zones of stimulation was 45 500 individual. Thus, benthic gain overshadowed benthic loss by a factor of about 2.2 times in New Bayou.

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